Ecological Economics 146 (2018) 35–43

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

The Challenge of Mitigating Climate Change through Forestry Activities: What Are the Rules of the Game?

G. Cornelis van Kooten

University of Victoria, Department of Economics, PO Box 1700, STN CSC, Victoria, BC V8W 2Y2, Canada

A R T I C L E I N F O

JEL Classification:
H23
Q23
Q42
Q54
G15

Keywords:
Climate change mitigation
Forest carbon offsets
Carbon life-cycle analysis
Biomass energy
Wood products versus cement and steel

A B S T R A C T

In this study, the price of carbon is used to incentivize a reduction in the release of CO_2 emissions and an increase in sequestration of CO_2 through forestry activities. Forest managers essentially have two options for increasing carbon sequestration (i.e., creating carbon offset credits): (1) avoid or delay harvest of mature timber; or (2) harvest timber and allow natural or artificial regeneration (with 'regular' or 'seed-selected' growing stock). A forest management model representative of the southern interior of British Columbia is described and used to examine forest conservation that prevents emissions of CO_2, and even-flow and commercial harvesting where timber is processed into long-lived wood products that store carbon and residuals for energy. The objective of the model is to maximize net discounted returns to commercial timber operations plus the benefits of managing carbon fluxes. The model tracks carbon in living trees, organic matter, and post-harvest carbon pools. It also includes various parameters related to the weighting of future carbon flows, anticipated price of carbon, whether and to what extent use of biomass reduces fossil fuel emissions from generating electricity or production of non-wood construction materials, et cetera. The results demonstrate that the decision about which forestry activities generate carbon offset credits and how many is essentially a political and not a scientific one.

1. Introduction

Economic incentives are the best way to encourage public and private forestland owners, managers, loggers and wood processors to consider the climate impacts of forest management decisions. With appropriate incentives, forests could be managed more or less intensively for their commercial plus carbon benefits or left unmanaged. With carbon markets, economic agents can be required to purchase carbon offsets for emissions to the atmosphere and receive carbon credits for CO_2 sequestered in ecosystem sinks, growing vegetation or product pools. For example, carbon credits can be issued for carbon entering wood product pools and then used to offset emissions from fossil fuels during harvesting and processing. Lumber and engineered wood products are the most important product pools, because technological advances in engineered products have led to the construction of state-of-the-art multipurpose and multi-story wood buildings that are now less vulnerable to fire and pests, and require less energy to heat or cool thereby further reducing CO_2 emissions (Green and Karsh, 2012).

To overcome issues related to measurement and monitoring, carbon offset credits/debits can be based on a forest management (growth and yield) model specified in advance plus observed changes in land use (van Kooten, 2009). The forest management model would specify the annual carbon uptake in the various components of the forest ecosystem from the time trees are planted until they are harvested, if at all. Each year, the landowner would receive a credit for the carbon removed from the atmosphere. At the time of harvest, the owner would purchase offsets based on the CO_2 released from decaying residues left on the site, decaying residues resulting from processing and manufacturing, and decaying short- and long-lived products. It will, however, be necessary to determine how much roundwood and other biomass is harvested and how this wood is utilized to establish how much carbon enters post-harvest pools. Decay rates for each carbon pool can be established a priori and the carbon fluxes resulting over infinite time discounted to the present to determine the credits to be purchased to cover emissions at the time of harvest.

This procedure seems reasonably straightforward, but it is fraught with pitfalls, the most obvious of which is the rate used to discount future carbon fluxes – the inevitable future releases of CO_2 from decaying wood products. As demonstrated in this paper, this is a political decision. But there are many more political decisions that establish the rules for awarding carbon offset credits. For example, it is possible to provide credits for the CO_2 emissions avoided when biomass is burned in lieu of fossil fuels, or credits for the emissions avoided from producing non-wood materials when wood substitutes for steel or concrete in construction, or even credits for the emissions avoided when heating wood buildings as opposed to non-wood ones.

E-mail address: kooten@uvic.ca.

http://dx.doi.org/10.1016/j.ecolecon.2017.10.002
Received 20 June 2017; Received in revised form 27 September 2017; Accepted 2 October 2017
Available online 10 October 2017

These are more controversial aspects of a forest carbon uptake scheme because it could result in double counting. When biomass substitutes for fossil fuels in the generation of electricity, the utility is no longer charged for the emissions associated with the burning of fossil fuels, which is a benefit counted outside forestry. The same is true of the emissions saved from not producing steel and cement when wood substitutes for non-wood materials in construction. If such benefits are counted elsewhere and not attributable to forestry activities, the only carbon savings that can be credited occur because carbon is stored in products.

On the other hand, if CO_2 emissions avoided are credited when bioenergy is burned instead of fossil fuels, then it is just as appropriate to credit the fossil fuel emissions avoided when wood substitutes for non-wood in construction (and fossil fuel emissions avoided when less energy is required to heat or cool wood buildings as opposed to concrete and steel ones). Importantly, inclusion of these avoided emissions is a political not scientific decision, but it influences the choice of forest strategy to mitigate climate change. Thus, economic agents must know the rules of the carbon game before making forestry decisions, and these rules are ultimately established by the political authority.

The current paper abstracts from the rules established by the IPCC (2000) for calculating carbon sequestration, because the rules do not take into account the carbon life-cycle as it applies, for example, to recent pressure on forest ecosystems to deliver biomass for generating electricity, and because the role of economic incentives is neglected. It contributes to the debate about how forestry activities might best be deployed to mitigate climate change. We compare carbon uptake, storage and release under various forest management strategies, including the possibility of 'leaving the forest unmanaged.' Importantly, we take into account the life-cycle of carbon through the vertical chain of processing wood. By valuing carbon, forest managers are incentivized to choose strategies that promote carbon sequestration and storage, but they would need to take the wood product substitution rate as given. By pricing carbon and specifying the 'rules of the game', forest managers are able to balance the trade-offs between leaving forests to grow and harvesting them for wood products, including bioenergy.

We proceed as follows. In the next section, we provide an economics perspective on the life-cycle of carbon in forestry. The model used in the study is then described in Section 3, followed by the results of various scenarios in Section 4. We conclude with a discussion of policy implications regarding the management of forests.

2. Economics of Carbon Fluxes

An important consideration when managing forests for climate mitigation relates to the timing of carbon fluxes. How do forest management activities and post-harvest uses of fiber affect the stream of CO_2 release to and removals from the atmosphere? While the mitigation objective might be interpreted to mean 'sequester the greatest amount of carbon in forest ecosystems and wood product pools,' this objective is not as straightforward as it might seem. There are two reasons: One relates to the life-cycle of carbon while the other relates to the emissions avoided when wood fiber is used in construction or as a fuel, and both relate to the urgency to address global warming (Johnston and van Kooten, 2015).

Scientists clearly favor the use of radiative forcing because "it provides a kind of *physically based discounting factor* by which the biomass emissions with deviating timing can be transformed into a permanent fossil carbon emission whose cumulative warming impact within a given time horizon is the same" (Helin et al., 2013, p.481, emphasis added). The concept of radiative forcing is not commonly used by policy analysts, as they would argue that "assessments of mitigation must go beyond just considering the C [carbon] pools in forest ecosystems: it is important to also consider C use and storage in HWPs [harvested wood products] and landfills, substitution of wood for more emissions-intensive products and fossil fuels, and land-use change involving forests. Such activities are highly interconnected, [and] … need to be based on an integrated assessment of the various mitigation possibilities" (Lemprière et al., 2013, pp.298, 301).

Canadian Forest Service (CFS) scientists (Kurz et al., 2013; Lemprière et al., 2013; Smyth et al., 2014) take a systems approach that measures the carbon fluxes associated with the interaction between human activities (planting, fertilizing, thinning, harvesting) and the forest ecosystem dynamics, including wildfire, pests, et cetera. A systems approach considers carbon stored in long-lived product pools, and CO_2 emissions avoided when wood replaces steel and cement in construction and/or wood biomass replaces fossil fuels in energy production.[1] The CFS scientists find that commercial harvesting of trees to produce wood products is generally preferred to storing carbon in unmanaged forests (Smyth et al., 2014 provide some exceptions), and that production of wood products leads to a greater carbon dividend than the use of wood biomass for energy. Indeed, Lemprière et al. (2017) find that intensive forest management could account for 9.8% to 14.7% of Canada's annual CO_2-emissions reduction target of 112 Mt CO_2 between 2014 and 2020, and at a cost of less than $50/t$CO_2$. At the provincial level, BC could rely on forestry activities to achieve 35% of its targeted emissions reduction by 2050 at a cost of less than $100/t$CO_2$ (Xu et al., 2017). Missing from these large-landscape scale studies are the economic incentives that landowners, logging companies and wood processors require to implement the needed activities. Importantly, the incentives must also include the carbon accounting rules – particularly substitution rates for emissions avoided and how carbon fluxes are to be weighted over time.

Economic agents need to know the carbon benefit or cost associated with the decisions they make regarding harvest utilization and logging methods (size of trees, residuals), transportation (roadside waste), processing (products to produce), and regeneration, among others. Subject to technical and institutional constraints, price signals determine how much timber is harvested and how much lumber, plywood, wood chips, et cetera, are produced. Whether through the issuance of carbon offset credits for sale in carbon markets or through a tax/subsidy scheme, the introduction of carbon prices signals agents to alter their harvesting practices, choice of product mix, and overall use of wood fiber. Agents need to know whether and how many carbon offsets they will earn when wood substitutes for fossil fuels in electricity generation, or when wood substitutes for concrete and cement in construction. They need to know how much carbon is credited to their account in each period if trees are left unharvested, or if they plant faster-growing trees. That is, economic agents need to know the rules of the game, and that may require the use of models to establish the carbon fluxes related to various forestry activities.

The length of time that incremental carbon is stored in forest ecosystems, product pools or in the atmosphere may be on the order of decades. Since the release of CO_2 to the atmosphere contributes to climate forcing, while removals do the opposite, there may be some urgency to remove CO_2 from the atmosphere to avoid climate forcing. Thus, the timing of emissions and removals of carbon are important, with current emissions and removals from the atmosphere more important than later ones (Helin et al., 2013, p.476). This is a policy decision and implies that carbon fluxes need to be weighted as to when they occur, with future fluxes discounted relative to current ones (Richards, 1997; Schlamadinger and Marland, 1999).

The weights used to discount future carbon fluxes can be thought of as discount rates that can be used to put into practice the urgency of policy to address climate change (Johnston and van Kooten, 2015). If global warming is not considered a problem, the economist might use a zero discount rate, in which case it really does not matter if biomass

[1] Concrete requires five times and steel 24 times more energy to produce than an equivalent amount of sawn softwood; wood is also five times more insulating than concrete and 350 times more than steel (Risen, 2014).

growth removes CO_2 from the atmosphere today or sometime in the future – it only matters that the CO_2 is eventually removed. If, on the other hand, global warming is an urgent problem, we would want to weight current reductions in emissions and removals of CO_2 from the atmosphere (current sequestration) much higher than those in future years. This is the same as discounting future uptake of CO_2, with higher discount rates suggesting greater urgency in dealing with global warming.

We measure the CO_2 that enters post-harvest wood product pools and is released over many decades as wood products decay as if it were released at the time of harvest. This is done by determining the carbon flux caused by decay in each future period after harvest, applying a weight (discount factor), denoted r_c, to the CO_2 flux in each of those periods, and aggregating the infinite sum. This weighted sum can then be credited at the time of harvest – the physical stream of carbon flux is discounted to the time of harvest. If the price of carbon is non-zero, the CO_2 emitted or accumulated at time of harvest, say t, is then multiplied by the price of carbon and, since the landowner receives payment (for uptake) or pays a penalty (for emissions) at time t, discounted to the present at the financial rate of discount. The weighted current carbon released from and stored in a post-harvest wood product pool is given by (see Appendix A for a proof):

$$V_{Crelease} = \left(\frac{d}{r_c + d}\right)\varepsilon C \text{ and } V_{Cstored} = \left(\frac{r_c}{r_c + d}\right)\varepsilon C, \tag{1}$$

where d is the rate at which the wood decays, C is the amount of carbon in harvested timber and ε is the proportion the timber entering the product pool. If $d = 0$ (no decay) then the amount of carbon released from products is also zero and all the carbon is retained regardless of the rate used to weight carbon. If $r_c = 0$, no carbon is stored because it is all released. The same reasoning applies to biomass burning and subsequent uptake through new growth. In that case, we determine $V_{Cstored}$ and compare that to the initial release of CO_2 from burning.

We apply these ideas to the Quesnel TSA – an important productive BC forest supplying timber for mills producing lumber for export. A key component of the model is how we apply the concept of urgency.

3. Managing for Carbon: A Management Model of Quesnel TSA

In this section, we adapt a forest management model developed by van Kooten et al. (2015) for a small forest in southeastern BC to the Quesnel Timber Supply Area (TSA) in the BC interior. We employ the existing forest inventory for the Quesnel TSA and the provincial government's TIPSY model to forecast timber growth and yield based on the topographical and environmental conditions of the forests in the interior of British Columbia (BC Ministry of Forests, Lands and Natural Resource Operations, hereafter MFLNRO, 2016).[2] The model maximizes net discounted returns to commercial timber operations (and sale of downstream products) plus the benefits of managing carbon fluxes. Unlike the CFS studies, we employ economic incentives to implement forest management activities that sequester carbon and specify the rules regarding how much carbon can be credited. In addition to wood for energy, we consider activities that cause carbon to enter various forest ecosystem and post-harvest wood product pools taking into account emissions avoided from not using steel and concrete.

3.1. Forest Management Model

Following van Kooten et al. (2015), let $x_{s,a,z,m,t}$ denote the hectares of timber species s of age a in zone z that are harvested in period t and regenerated according to regime m, which refers in this case to basic or enhanced silviculture post-harvest. Let $v_{s,a,z,m,t}$ be the associated total merchantable volume (m^3/ha) of the stand at time t that is to be converted to lumber, wood chips (used in pulp mills or manufacture of oriented-strand board and medium-density-fiber board, etc.), or for production of energy; and assume the stand's initial volume is given by $v_{s,a,z,m,0}$. Then we define total harvest in period t as follows:

$$H_t = \sum_{s=1}^{S}\sum_{a=1}^{A}\sum_{z=1}^{Z}\sum_{m=1}^{M} v_{s,a,z,t}x_{s,a,z,t},\ \forall\ t, \tag{2}$$

where S is the total number of tree species,[3] A the number of age classes, Z the number of zones and M the post-harvest regeneration options. Zones constitute a combination of eight bio-geoclimatic subzones and 17 slope categories, so there are effectively 136 different forestland types in the model. The time horizon is 200 years divided into decades, while age classes begin as 'bare' (recently harvested) and increase by decadal increments to old-growth (≥ 200 years). Finally, the land or rights owner decides when to harvest trees, which land types to harvest, and how much to harvest; following harvest, she must determine whether basic or enhanced regeneration is employed, where the latter employs 'improved' species of the same mix as that of the harvested sites.

We define the total costs (K_t) in period t as:

$$K_t = K_t^{\log} + K_t^{\text{haul}} + K_t^{\text{silv}} + K_t^{\text{admin}} + K_t^{\text{proc}}. \tag{3}$$

$K_t^{\log}$ are logging costs (\$/m^3) that vary by the size of trees; $K_t^{\text{haul}} = c^{\text{truck}} \times H_t$ are trucking costs (\$/m^3) that vary with harvest levels H_t (an average constant haul distance and truck speed is applied for convenience); K_t^{silv} are regeneration costs (\$/ha) that vary according to biogeoclimatic zone and regeneration option; and K_t^{admin} are administrative and development costs (\$/ha) that are assumed to be constant. Processing or manufacturing costs K_t^{proc} relate to sawmilling and production of engineered wood products.

Assuming that timber throughout the Quesnel TSA is relatively homogenous, the same proportion ε_1 of all the harvested timber is converted to lumber, a proportion ε_2 is sold as chips and a proportion ε_3 is used to generate electricity or used for space heating, while the remainder is left to decay at the harvest site. The price of chips is the same regardless of how chips are used. Let p_{lum}, p_{chip} and p_{fuel} be the respective fixed prices of lumber, chips and bioenergy fiber.

Finally, we need to account for carbon. First, assume that, since the price of fuel is fixed in the analysis as is the efficiency of equipment, CO_2 emissions (E_t) are fixed proportions of the logging, hauling and silvicultural costs. In addition, there are costs associated with processing logs into products. Thus, CO_2 emissions are derived as follows:

$$E_t = e_1K_t^{\log} + e_2K_t^{\text{haul}} + e_3K_t^{\text{silv}} + e_4K_t^{\text{proc}},\ \forall\ t, \tag{4}$$

where e_1, e_2, e_3 and e_4 are parameters that, respectively, convert the costs associated with logging, hauling, silvicultural and manufacturing/processing activities into CO_2 emissions.

Following Malmsheimer et al. (2011), we determine the amount of carbon that is sequestered in each period in the above-ground biomass (leaves, branches, litter) and soil organic matter. We denote the total carbon stored in the ecosystem at any given time, as measured in terms of CO_2, by C_t^{eco}. The CFS's Carbon Budget Model is used within TIPSY to track ecosystem carbon fluxes that vary with the growth of the forest.

We consider the carbon stored in four product pools – (i) lumber; (ii) engineered wood products made from wood chips; (iii) pulp from wood chips and other residuals; and (iv) logging, sawmill and other residues that are used to produce bioenergy (e.g., wood pellets for power

[2] TIPSY (Table Interpolation Program for Stand Yields) was developed to provide yield tables for stands under different management regimes using TASS (Tree and Stand Simulator) and economic data using SYLVER (Silviculture on Yield, Lumber Value, and Economic Return) (BC Ministry of Forests, Lands and Natural Resource Operations, 2016). It also tracks carbon using the Canadian Forest Service's Carbon Budget Model CBM-CFS3 (Kull et al., 2011).

[3] Each site is classified by a dominant and a secondary species. There are 11 species, of which seven are considered dominant and 10 secondary (some dominant species may be secondary species on other sites).

generation, biomass for heating).[4] In addition, the carbon stored in dead organic matter and material left at roadside is treated separately as is the carbon in living matter (which does not decay). Denote the rates of decay for each of the four product pools and the dead organic matter pool by d_1, d_2, d_3, d_4 and d_5, respectively, and assume that decay begins at the time of harvest. Then, from Eq. (1), the amount of carbon stored in the four pools as a result of harvest H_t is given as follows:

$$C_t^{product} = \varphi \sum_i \frac{r_c}{r_c + d_i} \varepsilon_i H_t,\ i \in \{\text{lumber, engineered products, pulp chips, residues/waste}\}, \tag{5}$$

where parameter φ (= 44/12) converts carbon to CO_2. Notice that C_t refers to the net CO_2 removed from the atmosphere at time t after taking into account future emissions from decay.

Lastly, we consider the avoided fossil fuel emissions when wood products substitute for non-wood products (viz., aluminum studs, concrete) in construction (Hennigar et al., 2008) or coal, say, in generation of electricity:

$$C_t^{ff} = \varphi\ \xi\ \varepsilon_1\ H_t, \tag{6}$$

where ξ is a parameter denoting the emissions avoided when wood substitutes for other products. Total carbon removed from the atmosphere at any time is then given by the sum:

$$C_t = C_t^{eco} + C_t^{product} + C_t^{ff}. \tag{7}$$

The constrained optimization problem can now be formulated as a linear programming model with the following objective:

$$NPV = \sum_{t=1}^{T} \beta^t \left[\left(\sum_{i=1}^{N} p_i \varepsilon_i \right) H_t - K_t - p_C (E_t - C_t) \right], \tag{8}$$

where p_C refers to the price of carbon ($/t$CO_2$), p_i to the price of forest product i, ε_i is the proportion of the harvest processed into product i, and $\beta = 1/(1 + r)$ is the financial discount factor, with r the discount rate on monetary values. For simplicity and given fixed product prices and proportions ε_i, we assume that the price of logs ($/m^3) ($= p_{lum}\, \varepsilon_{\text{lum}} + p_{eng}\, \varepsilon_{\text{eng}} + p_{pulp}\, \varepsilon_{\text{pulp}} + p_{fuel}\, \varepsilon_{\text{fuel}}$) is the value of interest in the objective function (8). Finally, it is important to recognize that parameter C_t^{ff} is embedded in C_t (see Eq. (6)); it refers to the CO_2 emissions avoided because of the reduced production of cement and steel if wood substitutes for these materials in construction, or if wood biomass substitutes for fossil fuels in the generation of electricity.

Objective function (8) is maximized subject to Eqs. (2), (3), (4) and (7), which define H_t, K_t, E_t and C_t, respectively, plus a variety of technical constraints that include growth functions, area constraints, et cetera. The latter relate to the limits on harvest imposed by the available inventory in any period as determined by tree species, bio-geoclimatic zones, slope and age characteristics; a total area constraint; growth from one period to the next (which is affected by management practices); reforestation options; limits on the minimal merchantable volume that must stocked before harvest can occur; sustainability constraints (viz., sustainable management certification standards); non-negativity constraints; and other constraints relating to the specific scenarios that are investigated (including avoided emissions related to substitution of wood for non-wood in construction and wood biomass for fossil fuels in energy). The constrained optimization model is constructed in GAMS (General Algebraic Modeling System) and solved using the CPLEX solver (Rosenthal, 2008).

3.2. Study Area and Data Description

British Columbia is Canada's most important timber producing province with 95 million ha of forestland (27.3% of Canada's total), a harvest of 66.5 million m^3 (43.4%), and exports of more than $10.8 billion (50.4%) (Natural Resources Canada, 2016). The Quesnel TSA is located in the Northern Cariboo Forest Region in the Southern Interior of BC and covers some 1.4 million ha, of which 965,700 ha are in the harvest land base, consisting of Lodgepole pine (85%), spruce (10%), Douglas-fir (3%) and a variety of other species (Snetsinger, 2011). We distinguish forest sites in the Quesnel TSA according to the following characteristics: two main zones bio-geoclimatic zones, Montane Spruce (MS) and Sub-Boreal Pine Spruce (SBPS), with costs of regeneration higher in MS; four subzones; 17 slope classes, seven major species; 10 secondary species, and 21 age class. While this potentially gives nearly 200,000 combinations of site possibilities, species other than pine and spruce rarely occur as major or secondary species, so Aspen and two types of Birch were classified together as were Douglas fir and Balsam.

To keep the model manageable, we used GIS data for Quesnel TSA to identify 538 sites, although the proportions of major and secondary species were not available from the GIS data. We then varied the percentages of major and secondary species, and used the TIPSY model to estimate growth and yield for 200 years (using a decadal time step) and for two treatments after harvest – stands regenerated with fast-growing or enhanced ('seed-selected') stems planted over a two-year period or regenerated with natural growing stock (basic silviculture) within six years of harvest. In this way, the 538 sites were expanded into 6205 stands covering an area of 20,266.4 ha. The CFS's Carbon Budget Model was used to track carbon fluxes and stocks in living and dead biomass in the forest ecosystem.

The costs of converting standing trees into lumber, sawmill residues and chips is the sum of the harvesting costs, road and infrastructure costs, transportation costs, manufacturing costs, and costs of post-harvest treatment of the site (basic versus enhanced regeneration). These are also available from TIPSY and are summarized in Table 1. Average lumber prices have varied from a low of $70/m^3 in 2009 to more than $170/m^3 before the recession and about $160/m^3 in 2015. The price of engineered wood products is assumed to be $200/m^3. It is assumed that the only processing costs relate to sawmilling and the production of engineered products such as OSB; these costs are provided in Table 1. Sawmilling leads to the production of lumber and sawmilling residues that can be used to produce chips, engineered wood products or biomass fuel (discussed below).

Wholesale electricity price data are available only for Alberta, where electricity traded for an average price of $49.50/MWh in 2014; because biomass is a renewable energy source and often granted implicit or explicit subsidies, we assume the BC producer would receive a subsidized price of $75/MWh, which translates into a price for wood residues of $155/m^3. The price of wood chips is assumed to be $145/m^3. Prices used in the study are also given in Table 1.

Given the study region already includes logging roads and other infrastructure as the area has been harvested in the past, fixed costs are lower than might be the case in other mountainous regions. Transportation costs vary with distance, while post-harvest treatment costs vary by bio-geoclimatic zone and regeneration type. The information on these costs is provided in Table 1.

A typical distribution of lumber and residues in sawmilling is available for the BC interior from the annual mill survey (BC Ministry of Forests, Lands and Natural Resource Operations (MFLNRO), 2015). In 2014, the total interior harvest was 48,074,000 m^3, with 39,531,000 m^3 (82.2%) processed by lumber mills and 4343,000 m^3 (9.0%) by veneer and OSB mills; the remainder went directly to pulp mills for chipping (1.3%), chip and other mills (5.1%), and log exports (2.4%, 1.15 million m^3). Of the log volume allocated to lumber mills, 44.4% was processed into lumber with 53.4% constituting sawmill residues (sawdust and shavings) and 2.2% shrinkage. Neglecting shrinkage because TIPSY output is assumed to account for shrinkage and assuming no log exports, the log harvest is adjusted to 46,924,000 m^3, which is then allocated as indicated in Table 2. Sawdust is burned on site to generate heat or electricity or made into wood pellets. Chips are used to make pulp, produce OSB and other engineered wood products, or manufacture wood pellets to generate electricity.

[4] Sawmill residues are often burned on site (at a mill) to reduce energy costs.

Table 1
Price, cost, harvest and other parameters, Quesnel TSA[a].

General parameters		Transportation	
Monetary discount rate (%)	2.5%	Fixed costs ($/ha)	295.0
Carbon discount rate (%)	0, 1.5, 15	Hauling ($/$m^3$ per cycle hour)	6.67
Price lumber ($/$m^3$)	160.0	Hauling distance (km)	150
Price engineered products ($/$m^3$)	200.0	Speed of trucks (km/h)	50
Price chips ($/$m^3$)	145.0	Silviculture regeneration ($/ha)	
Price of fuel ($/$m^3$)	155.0	Basic (SBPS, MS)	1000, 1200
		Enhanced (SBPS, MS)	1500, 1800
Logging costs ($/$m^3$)		Manufacturing costs ($/$m^3$)[b]	
Non-variable	22.20	Sawmilling per harvested log	72.00
Variable	2.04–0.005 V if V < 251 m^3 0.79–0.001 V if V ≥ 251 m^3	Engineered products (over-and-above sawmilling costs)	50.00

[a] Source: Data on prices come from Random Lengths (2016). Cost data come from Wiltshire and Associates Forestry (2014); Renzie and Han (2008); and TIPSY model (BC Ministry of Forests, Lands and Natural Resource Operations, 2016). Conversion factors are from http://www.globalwood.org/tech/tech_wood_weights.htm [accessed November 21, 2016].
[b] Milling costs are $335 per thousand board feet (mbf). Log cost ($/$m^3$) = [lumber recovery (215 bf/m^3)] × $0.335/bf = $72.00/$m^3$. Costs for engineered wood products from chips are over and above sawmilling costs.

Table 2
Disposition of harvested logs: production of lumber, sawmill residues and other products, BC Interior, 2014[a].

Category of use and sub-category	Volume ('000 s m^3)	Proportion of harvest (%)[b]	Within category (%)
Lumber	*18,174.6*	*38.7*	
Sawmill residues	*21,335.4*	*45.5*	
• Sawdust	12,161.2	25.9	57.0
• Chips	9174.2	19.6	43.0
Other products	*7414.0*	*15.8*	
• Engineered wood products	4343.0	9.3	58.6
• Chipped in pulp mills	620.0	1.3	8.4
• Other chips from whole logs	2451.0	5.2	33.1
Logging residues & roadside waste[c]	*0*	n.a.	
Total harvest	46,924.0		

[a] Data from annual mill report for 2014 (BC Ministry of Forests, Lands and Natural Resource Operations (MFLNRO), 2015), adjusted to remove shrinkage and log exports.
[b] Numbers may not add to 100% due to rounding.
[c] Logging residuals are left in the forest and as are roadside wastes, which result from trimming logs to fit trucks optimally. These are too costly to remove (Stennes et al., 2010).

Lumber is the most valuable wood product and sawmill residues are the most important source of residues for pulp mills, engineered wood manufacturers and bioenergy producers. Since lumber recovery from harvested logs varies by species, age and site characteristics, the TIPSY model is used to obtain the volumes of lumber, sawmill residues (m^3), and other residuals (m^3) for each of these characteristics. Since TIPSY provides lumber volume in thousands of board feet (mbf), the board feet measure is converted to m^3 using the average conversion factor of 1.61 m^3/mbf available from the latest mill survey (BC Ministry of Forests, Lands and Natural Resource Operations (MFLNRO), 2015). As a check, a comparison of the TIPSY data for Quesnel used here and the average observed conversion factors for the BC interior from the 2014 mill survey indicates they are almost identical.

We find that pulp mills in the BC interior consumed 20.038 million m^3 of wood fiber, while pellet plants consumed 4.366 million m^3. This implies that pulp mills and pellet plants respectively consumed 69.7% and 15.2% of the total available residual fiber in the interior (28,749,400 m^3), with engineered wood manufacturers employing the remaining 15.1%. Thus, in our model, we allocate 42.7% of available timber to pulp production, with the remainder allocated to lumber (38.7%), wood pellets (9.3%) and engineered products (9.3%); engineered products and lumber are employed in construction, with lumber potentially used to produce cross-laminated timber (CLT), the longest-lived product.

The CO_2 released when producing a megawatt hour (MWh) of electricity varies by fuel type. Natural gas releases 0.55 tCO_2/MWh of power, while coal releases 0.94 tCO_2/MWh. Burning wood biomass provides 6.6 GJ of heat per m^3 if the moisture content is 40% (Kofman, 2010), which translates into 1.83 MWh/m^3. Thus, burning wood in lieu of natural gas would save 1.01 tCO_2/m^3 (= 0.55 tCO_2/MWh × 1.83 MWh/m^3), while it would save 1.72 tCO_2/m^3 if bioenergy replaced coal. Wood burning is considered carbon neutral in legislation, so emission reductions from burning wood in lieu of a 50–50 mix of natural gas and coal to generate electricity amount to 1.365 tCO_2/m^3. Finally, the CO_2 emission rates and decay rates for various components and product pools used in this study are provided in Table 3.

4. Managing for Carbon: Results

Carbon outcomes depend on the management regime chosen, which, in turn, depends on the price of carbon, biophysical constraints and sustainability requirements. Outcomes also depend on the weight attached to future carbon fluxes – on the perceived urgency of addressing climate change. Finally, the carbon flux is impacted by the extent to which emissions avoided from fossil fuel burning when wood biomass is used to generate electricity and/or wood substitutes for non-wood in construction. We used the forest management model of the Quesnel TSA to examine various scenarios based on the following three management regimes:

1. No harvest (NH) or forest conservation – not harvesting the forest whatsoever;
2. Even-flow management (EF) – harvests in any decade cannot vary by > 10% from the endogenously determined harvest in the first decade; and

Table 3
Rates of CO_2 emissions and decay rates for various forest carbon pools.
Source: Healey et al. (2009) and authors' calculations based on estimated half-lives of wood products.

Carbon emissions	Value	Item	Value
Activity (tCO_2/m^3)		Decay rate of	
Harvesting (tCO_2/m^3)	0.01173	Dead organic matter	0.0718
Trucking (tCO_2/m^3)	0.000078	Softwood lumber	0.0082
Production of		Engineered wood products	0.0080
Sawlogs (tCO_2/m^3)	0.0293	Chips and pulp wood	0.0234
Engineered wood (tCO_2/m^3)	0.0660	Fuel[b]	1.0
Pulp wood (tCO_2/m^3)[a]	0.1000	Biofuel[b]	0.7

[a] Average of mechanical and chemical pulp.
[b] Assumed decay rates for fuel and biofuel indicate that, respectively, 100% and 70% of the CO_2 is emitted in the first year after harvest.

Table 4
Opportunity cost of creating carbon offset credits C$ per tCO_2[b].

Scenario[a]	NH → EF	EF → NH	NH → CM	CM → NH	EF → CM	CM → EF
P_c = 0, r_c = 0%	n.a.	43.36	$531.75	n.a.	14.13	n.a.
P_c = 0, r_c = 1.5%	n.a.	161.07	n.a.	154.47	n.a.	138.76
P_c = 0, r_c = 15%	n.a.	1223.56	n.a.	440.81	n.a.	159.33
P_c = 50, r_c = 0%	217.43	n.a.	$40.71	n.a.	12.55	n.a.
P_c = 50, r_c = 1.5%	n.a.	216.07	n.a.	280.24	n.a.	1557.60
P_c = 50, r_c = 15%	n.a.	1237.75	n.a.	441.91	n.a.	159.22
P_c = 0, r_c = 1.5%, lo sub	4490.76	n.a.	n.a.	964.39	n.a.	221.47
P_c = 50, r_c = 1.5%, lo sub	732.90	n.a.	$829.33	n.a.	1302.62	n.a.
P_c = 50, r_c = 1.5%, hi sub	32.27	n.a.	$39.01	n.a.	92.25	n.a.

[a] Scenarios are described in the text. A 2.5% rate of discount is applied to monetary values.
[b] n.a. indicates that the shift indicated results in a reduction in discounted carbon.

3. Commercial management (CM) – harvest is unconstrained except that areas harvested must be regenerated using basic or enhanced regeneration (as is the case under even-flow management), with only product and carbon prices as incentives.

For each management regime, we consider carbon prices of $0 and $50 per tCO_2, and carbon discount rates of 0%, 1.5% and 15.0%, which represent 'no urgency', 'some urgency' and 'great urgency' in mitigating climate change. In addition, we consider three cases that include reduced emissions from substituting biomass for fuel in generating electricity (Table 4); in two of these we assume a low ability to substitute wood products for non-wood in construction ('lo sub') and one where substitution is high ('hi sub'). In the latter case, we implicitly count the saved emissions from not producing steel or concrete. Even so, substitution rates of 0.25 tCO_2 per m^3 (lo) and 2.5 tCO_2/m^3 (hi) are well below the 3.3 tCO_2/m^3 found by Hennigar et al. (2008).

The results for nine scenarios are provided in Figs. 1 and 2 and Table 4. The total net (discounted) carbon produced by each scenario is provided in Fig. 1. If climate change is considered an urgent policy issue (carbon fluxes discounted at 15%), forestry activities in the BC interior do little to mitigate climate change. Forest conservation essentially continues to store the carbon already in the ecosystem and future contributions to ecosystem carbon are too distant to be considered, while total carbon attributable to even-flow or commercial management is essentially zero because the CO_2 emissions released early on as a result of logging, transportation and processing offset the discounted future carbon sequestered by fast-growing (young) trees or shifted into long-lived products.

At low carbon discount rates, the benefit of one management regime over another depends on carbon prices and the degree to which one counts carbon emissions avoided because wood substitutes for carbon-intensive products in construction or bioenergy for fossil fuels in electricity generation. The carbon offset credits created will depend on the baseline management regime that is chosen since offsets are counted against a baseline. It is clear from Fig. 1 that the choice of a baseline scenario is crucial to the determination of the carbon offsets. The most carbon credits that might be generated by the forest strategies in this study are unlikely to exceed 4 Mt CO_2, and this would entail a switch from conservation (NH) to commercial management (CM), as indicated in the last scenario in Fig. 1. This translates into a net discounted overall carbon benefit of < 200 tCO_2 per hectare. What might be the associated cost of sequestering carbon? This information is provided in Table 4.

First suppose future carbon fluxes are not discounted. Then commercial exploitation is always preferred to forest conservation (NH) and EF management (Table 4), although NH is preferred to EF if carbon is unpriced. When future carbon fluxes are discounted, conservation is always preferred to EF and CM, with EF also preferred to CM, regardless of the carbon price. The reason is that early emissions of CO_2 associated with logging, transportation and processing under CM exceed the discounted future carbon storage benefits.

The balance sheet changes dramatically when carbon is priced and one attributes saved CO_2 emissions in other sectors to forestry. In particular, CM is the preferred management regime followed by EF if one credits emissions avoided in the production of concrete and steel when wood substitutes for non-wood in construction (0.25 to 2.5 tCO_2/m^3) plus emissions avoided when wood substitutes for fossil fuels in electricity production (1.365 tCO_2/m^3). Indeed, the costs of mitigating climate change in BC's interior are quite reasonable for a carbon price of $50/$tCO_2$ and carbon discount rates of 0% (fourth row in Table 4) and 1.5% in the 'hi sub' scenario (last row in Table 4). The costs could be even lower if higher substitution values (> 3.0 tCO_2/m^3) are employed. Of course, results assume wood burning is carbon neutral (no CO_2 emissions from wood burning are counted against the forestry activity) and that saved emissions from not producing steel and concrete are attributable only to forestry.

Decision makers are generally not interested in total discounted net carbon. Rather, they are interested in carbon fluxes at various times, particularly in the next decade or two. This is provided for selected scenarios (with r_c = 1.5% and p_c = $50/$tCO_2$) in Fig. 2. Commercial forestry results in negative carbon uptake in the first decade as a result of high rates of harvest as the manager seeks to liquidate timber and

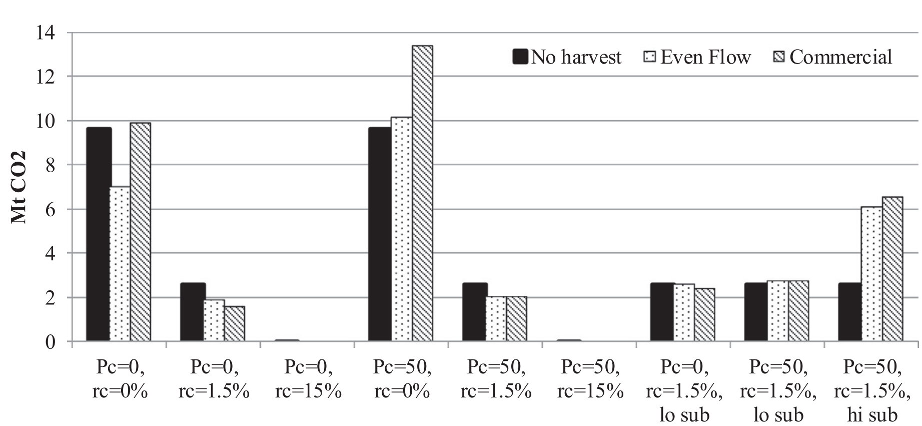

Fig. 1. Levels of carbon sequestration or carbon offsets created, various scenarios (Mt CO_2).

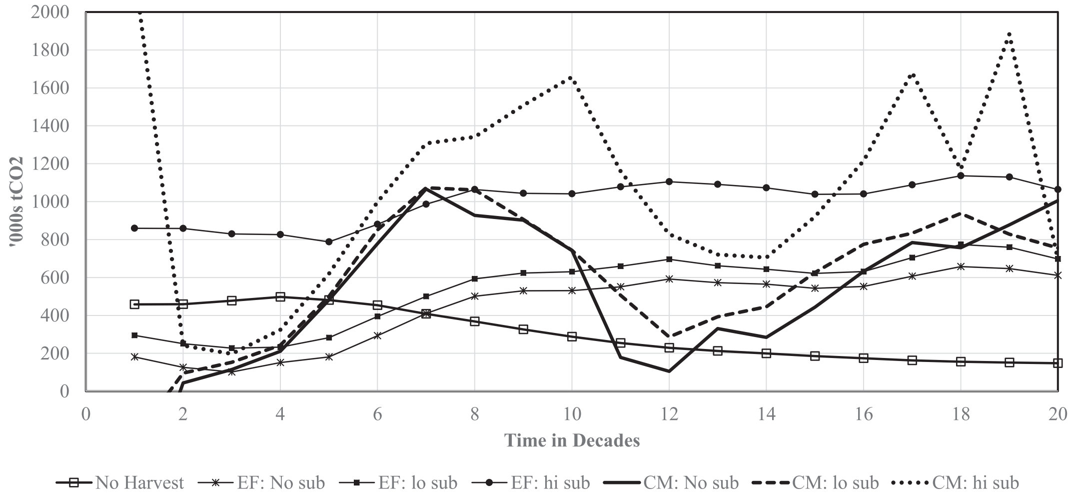

Fig. 2. Discounted CO_2 uptake per decade for non-harvested, even-flow and commercially managed forests; 1.5% carbon discount rate; 2.5% monetary discount rate; carbon price = \$50/tCO_2; 1.37 tCO_2/m^3 credit for bioenergy-for-coal substitution; and credits of 0.25 tCO_2/m^3 (lo) and 2.5 tCO_2/m^3 (hi) for reduced emissions elsewhere when wood substitutes for non-wood in construction.

convert land to faster growing trees. Only when the substitution of wood for non-wood in construction is credited at 2.5 tCO_2/m^3 does CM lead to a high rate of carbon flux in the first decades, only to decline substantially as harvest levels in subsequent decades fall. Indeed, with the exception of the CM and EF scenarios where wood for non-wood substitution receives a high credit, NH leads to higher carbon uptake in the first four decades. It is not surprising, therefore, that the decision maker might well favor forest conservation (see also Smyth et al., 2014).

Accreditation of carbon offsets for the CO_2 emissions avoided when wood substitutes for non-wood in construction and power generation is an important climate change mitigation policy. It causes a commercial operator to create carbon offset credits (reduce emissions), especially early in the time horizon (due to discounting), thereby lowering atmospheric CO_2 to a greater extent than the conservationist. The commercial operator manages the forest to maximize income not only from sale of forest products but also the revenue from storing carbon in the ecosystem through sequestration and silvicultural management, and from producing long-lived products with low rates of decay. If the substitution parameter is sufficiently high, CM will be the preferred strategy for mitigating climate change in all circumstances.

When a forest reaches maturity (after about 15 decades), it sequesters little carbon because biomass decay offsets carbon uptake in new growth (Fig. 2). In drier regions, mature forests are susceptible to wildfire, pests and disease that could release large amounts of carbon, as illustrated by the devastation caused by mountain pine beetle and wildfires in the BC interior. If the risk of natural disturbance is high, and if the carbon released as a result is charged to the forest manager/owner, the decision maker may be much more prone to harvest trees to avoid risk of loss. Therefore, if carbon is priced, the decision maker will harvest a mature forest and store carbon in products while regenerating the site so new growth sequesters carbon at a faster rate than leaving the forest unharvested.

5. Concluding Discussion

There are many ways in which forestry activities can mitigate climate change, but some are more effective than others, some preclude others, and some are less cost-effective than others. Perhaps not unexpectedly, some forestry activities might actually contribute to global warming when compared to a baseline scenario. When two or more forest management options are compared, assumptions regarding the accreditation of carbon fluxes, and whether to count emissions saved when wood substitutes for non-wood materials in construction or fossil fuels in power generation and to what extent, will determine which forest management strategies contribute to climate mitigation, and to what extent. The choice of strategy is also impacted by the perceived urgency of taking action to mitigate climate change, which affects the weighting of future carbon fluxes. Assuming that climate change mitigation is to be addressed through forestry activities, the forest manager needs to know the rules of the game before choosing a forest management strategy, because the rules regarding how carbon fluxes are counted affect decisions regarding which forest activities to undertake.

Within this discussion of the rules of the game, some general conclusions follow: First, it is not clear that forests should ever be conserved in perpetuity, partly because of their eventual susceptibility to natural disturbance and partly because carbon can be stored in post-harvest pools. Forest conservation might be a good strategy in the short run if the forests are not at full maturity, but is unlikely a good long-run option because with commercial forestry carbon is retained in wood products while regenerated forests grow more rapidly than mature ones with growth enhanced by planting higher quality seedlings.

Second, wood burning is not carbon neutral if there is urgency to address climate change. Wood burning is carbon neutral if future carbon is not discounted (r_c = 0%), but then so is coal burning.

Third, counting CO_2 emissions avoided when wood burning substitutes for fossil fuels results in offsets, but this leads to double counting because the electricity entity will count the emissions avoided from not burning coal or gas toward its targets. We find that not counting these emission savings reduces offset credits by 8.3%. Likewise, counting CO_2 emissions avoided when wood substitutes for non-wood materials in construction leads to more carbon offset credits, but results in double counting just as with wood burning. Therefore, although carbon stored in wood is properly credited to forestry activities, the carbon credits created because emissions are reduced in another sector should not be attributed to forestry even though IPCC rules might permit this.

Fourth, the decision regarding natural disturbance is a political one, although it can affect the amount of CO_2 in the atmosphere. Thus, in response to research by Kurz et al. (2008) showing that Canada's forests are a net carbon source if natural disturbances are taken into account, the government's commitment to the Paris Agreement concluded that “Canada will exclude emissions from natural disturbances.”[5] Although not explicitly demonstrated in this paper, this tilts the playing field toward conservation and

[5] This is the last statement in Canada's INDC submission to the UNFCC available at [accessed September 27, 2017]: http://www4.unfccc.int/Submissions/INDC/Submission%20Pages/submissions.aspx.

away from commercial or even-flow management.

Finally, how many offset credits do forestry activities create? Since we need a baseline and then weight credits as to when they occur, forestry activities generally create few offset credits. Indeed, the more urgent policy makers consider climate change to be, the fewer offset credits are realizable because future carbon uptake by forests is counted less today.

The overall conclusion from this study is that the decision about which forestry activities generate carbon offset credits and how many is essentially a political and not a scientific one. Although constrained by the biophysical realities of timber growth, forest ecosystem dynamics and processing technologies, the analyst has sufficient room to demonstrate that any forest management regime, whether forest conservation, even-flow management, commercial exploitation or some mix of strategies, is preferred to another for mitigating climate change.

Acknowledgements

An earlier version of this paper was presented at the American Geophysical Union Fall Meetings in San Francisco, December 2016, and the IUFRO 125th Anniversary conference in Freiburg, Germany, September 20, 2017. Funding was partially provided by a NSERC Discovery Grant #RGPIN 2015-03959 and a Tier One Canada Research Chair Program.

Appendix A. Proof of the CO_2 Measure of Infinite Release of Carbon from a Post-Harvest Wood Carbon Pool

Let r_c be the rate used to weight (discount) physical carbon, d be the rate at which carbon enters into atmosphere from the decay in the post-harvest carbon pool, and ε is the proportion of carbon that goes into the wood product sink at harvest time. At the time of harvest, how much carbon can we count going into a product sink? After one year, the amount of carbon going into the atmosphere is given by $d \times \varepsilon \times$ C, where C is the carbon in harvested timber. In the second year, the amount of carbon going into the atmosphere is given by $d(1–d)\,\varepsilon$ C; in the third year, carbon escaping to the atmosphere because of decay equals $d\,(1–d)^2\,\varepsilon$ C. The stream of carbon entering the atmosphere is given by:

$$d\,\varepsilon\,C + d\,(1-d)\,\varepsilon\,C + d\,(1-d)^2\,\varepsilon\,C + \ldots = [1 + (1-d) + (1-d)^2 + (1-d)^3 + \ldots]\,d\,\varepsilon\,C. \tag{1}$$

However, we need to weight the stream of carbon release. So let the stream of carbon release over n periods be:

$$V_n = \frac{d\varepsilon C}{1+r_c} + \frac{d(1-d)\varepsilon C}{(1+r_c)^2} + \frac{d(1-d)^2\varepsilon C}{(1+r_c)^3} + \frac{d(1-d)^3\varepsilon C}{(1+r_c)^4} + \ldots + \frac{d(1-d)^{n-1}\varepsilon C}{(1+r_c)^n}. \tag{2}$$

Multiply both sides by $(1–d)/(1 + r_c)$:

$$\frac{1-d}{1+r_c}V_n = \frac{d(1-d)\varepsilon C}{(1+r_c)^2} + \frac{d(1-d)^2\varepsilon C}{(1+r_c)^3} + \frac{d(1-d)^3\varepsilon C}{(1+r_c)^4} + \ldots + \frac{d(1-d)^{n-1}\varepsilon C}{(1+r_c)^n} + \frac{d(1-d)^n\varepsilon C}{(1+r_c)^{n+1}}. \tag{3}$$

By subtracting Eq. (3) from Eq. (2), we get:

$$\frac{r_c+d}{1+r_c}V_n = \frac{d\varepsilon\, C}{(1+r_c)} - \frac{d(1-d)^n\varepsilon\, C}{(1+r_c)^{n+1}} = \left(\frac{1}{1+r_c}\right)\left(1 - \frac{(1-d)^n}{(1+r_c)^n}\right)d\varepsilon C. \tag{4}$$

Thus,

$$V_n = \left(\frac{1}{r_c+d}\right)\left(1 - \frac{(1-d)^n}{(1+r_c)^n}\right)d\varepsilon C. \tag{5}$$

Finally, let $n \to \infty$ so that

$$V_{Crelease} = \lim_{n\to\infty} V_n = \left(\frac{d}{r_c+d}\right)\varepsilon C. \tag{6}$$

Notice that if $r_c = 0$, then all the stored carbon is released. That is, regardless of the decay rate (d), all of the carbon eventually is released from products through decay. Only if $d = 0$, so there is no decay, is the amount of carbon released from products also zero.

Since V is the discounted release of carbon at the time of harvest, the amount stored at time of harvest is given by:

$$V_{Cstored} = \varepsilon\, C - V = \left(1 - \frac{d}{r_c+d}\right)\varepsilon\, C = \left(\frac{r_c}{r_c+d}\right)\varepsilon C. \tag{7}$$

If $r_c = 0$, then no carbon is stored because it is all released (see above). If $d = 0$, then all the carbon is retained regardless of the rate used to weight carbon.

References

BC Ministry of Forests, Lands and Natural Resource Operations, 2016. Growth and yield modelling. April 5. Victoria. https://www.for.gov.bc.ca/hts/growth/download/download.html, Accessed date: 20 October 2016.

BC Ministry of Forests, Lands and Natural Resource Operations (MFLNRO), 2015. Major Primary Timber Processing Facilities in British Columbia, 2014. November. Competitiveness and Innovation Branch, Victoria (51 pp).

Green, M., Karsh, E., 2012. The case for tall wood buildings: how mass timber offers a safe, economical, and environmentally friendly alternative for tall building structures. Wood Enterprise Coalition, Vancouver, BChttp://cwc.ca/wp-content/uploads/publications-Tall-Wood.pdf, Accessed date: 26 April 2016 (February 22. 237 pp).

Healey, S.P., Blackard, J.A., Morgan, T.A., Loeffler, D., Jones, G., Songster, J., Brandt, J.P., Moisen, G.G., DeBlander, L.T., 2009. Changes in timber haul emissions in the context of shifting forest management and infrastructure. Carbon Balance Manag. 4, 9. http://dx.doi.org/10.1186/1750-0680-4-9.

Helin, T., Sokka, L., Soimakallio, S., Pingoud, K., Pajula, T., 2013. Approaches for inclusion of forest carbon cycle in life cycle assessment – a review. Glob. Change Biol. Bioenergy. 5, 475–486.

Hennigar, C.R., MacLean, D.A., Amos-Binks, L.J., 2008. A novel approach to optimize management strategies for carbon stored in both forest and wood products. For. Ecol. Manag. 256 (4), 786–797.

IPCC, 2000. In: Watson, R.T., Noble, I.R., Bolin, B., Ravindranath, N.H., Verardo, D.J., Dokken, D.J. (Eds.), Land Use, Land-Use Change and Forestry. Special Report. Cambridge University Press, Cambridge, UK. http://www.ipcc.ch/ipccreports/sres/land_use/index.php?idp=0 (375 pp).

Johnston, C.M.T., van Kooten, G.C., 2015. Back to the past: burning wood to save the globe. Ecol. Econ. 120 (December), 185–193.

Kofman, P.D., 2010. Units, conversion factors and formulae for wood for energy. COFORD Connects Harvesting/Transportation No.21. Dublin: Dep. of Agriculture, Fisheries & Food. http://www.coford.ie/media/coford/content/publications/projectreports/cofordconnects/ht21.pdf, Accessed date: 3 November 2016.

Kull, S.J., Rampley, G.J., Morken, S., Metsaranta, J., Neilson, E.T., Kurz, W.A., 2011.

Operational-scale Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) Version 1.2: User's Guide. CFS Technical Bulletin. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, AB (344 pp).
Kurz, W.A., Stinson, G., Rampley, G.J., Dymond, C.C., Neilson, E.T., 2008. Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain. PNAS 105 (5), 1551–1555.
Kurz, W.A., Shaw, C.H., Boisvenue, C., Stinson, G., Metsaranta, J., Leckie, D., Dyk, A., Smyth, C., Neilson, E.T., 2013. Carbon in Canada's boreal forest — a synthesis. Environ. Rev. 21, 260–292.
Lemprière, T.C., Kurz, W.A., Hogg, E.H., Schmoll, C., Rampley, G.J., Yemshanov, D., McKenney, D.W., Gilsenan, R., Beatch, A., Blain, D., Bhatti, J.S., Krcmar, E., 2013. Canadian boreal forests and climate change mitigation. Environ. Rev. 21, 293–321.
Lemprière, T.C., Krcmar, E., Rampley, G.J., Beatch, A., Smyth, C.E., Hafer, M., Kurz, W.A., 2017. Cost of climate change mitigation in Canada's forest sector. Canadian Journal of Forest Research 47 (5), 604–614. http://dx.doi.org/10.1139/cjfr-2016-0348.
Malmsheimer, R.W., Bowyer, J.L., Fried, J.S., Gee, E., Izlar, R.L., Miner, R.A., Munn, I.A., Oneil, E., Stewart, W.C., 2011. Managing forests because carbon matters: integrating energy, products, and land management policy. J. For. 109 (7S), 7–50.
Natural Resources Canada, 2016. The State of Canada's Forests. Annual Report 2016. Her Majesty the Queen in Right of Canada, Ottawa, ON (72 pp.).
Random Lengths, 2016. Forest Product Market Prices and Statistics. 2015 Yearbook. Random Lengths Publications, Eugene, OR.
Renzie, C., Han, H.-S., 2008. Harvesting productivity and cost of clearcut and partial cut in interior British Columbia, Canada. J. For. Sci. 24 (1), 1–14.
Richards, K.R., 1997. The time value of carbon in bottom-up studies. Crit. Rev. Environ. Sci. Technol. 27 (Special Issue), S279–292.
Risen, C., 2014. The world's most advanced building material is … wood. Popular science. http://www.popsci.com/article/technology/world's-most-advanced-building-material-wood, Accessed date: 3 May 2017.
Rosenthal, R.E., 2008. GAMS – A User's Guide. GAMS Development Corp, Washington, DC.
Schlamadinger, B., Marland, G., 1999. Net effect of forest harvest on CO_2 emissions to the atmosphere: a sensitivity analysis on the influence of time. Tellus 51B, 314–325.
Smyth, C.E., Stinson, G., Neilson, E., Lemprière, T.C., Hafer, M., Rampley, G.J., Kurz, W.A., 2014. Quantifying the biophysical climate change mitigation potential of Canada's forest sector. Biogeosciences 11, 3515–3529.
Snetsinger, J., 2011. Quesnel Timber Supply Area. Rationale for Allowable Annual Cut (AAC) Determination. Effective January 11, 2011. Report by the Chief Forester. BC Ministry of Forests, Mines and Lands, Victoria, BC (38 pp).
Stennes, B., Niquidet, K., van Kooten, G.C., 2010. Implications of expanding bioenergy production from wood in British Columbia: an application of a regional wood fibre allocation model. For. Sci. 56 (4), 366–378.
van Kooten, G.C., 2009. Biological carbon sinks: transaction costs and governance. For. Chron. 85 (3), 372–376.
van Kooten, G.C., Bogle, T., de Vries, F., 2015. Forest carbon offsets revisited: shedding light on darkwoods. For. Sci. 61 (2), 370–380.
Wiltshire and Associates Forestry, 2014. The cost of forest operations. http://www.wiltshireforestry.com/documents/Lecture11TheCostofForestOperations.pdf, Accessed date: 13 January 2017.
Xu, Z., Smyth, C.E., Lemprière, T.C., Rampley, G.J., Kurz, W.A., 2017. Climate change mitigation strategies in the forest sector: biophysical impacts and economic implications in British Columbia, Canada. Mitig. Adapt. Strateg. Glob. Chang. 1–34.